GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF RESEARCH ADMINISTRATION

RESEARCH PROJECT INITIATION

Date: October 8, 1973

Project Title: Analytical Investigation of External Burning Behind Bluff-Base Axisymmetric Bodies

Project No: E-16-636

Principal Investigator: Dr. W. C. Strahle

Sponsor: U. S. Army Research Office - Durham

Agreement Period: From 10/1/73 Until 9/30/76

Type Agreement: Contract No. DAHC04-73-C-0038

Amount: $49,381.00

Reports Required: Semi-Annual Progress Reports; Final Technical Report

Sponsor Contact Person (s):

Technical Matters

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Contractual Matters

(Thru O.R.A.)
Mr. Jack L. Harless
Contracting Officer

Assigned to: School of Aerospace Engineering

COPIES TO:

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- Other

RA-3 (6-71)

GEORGIA INSTITUTE OF TECHNOLOGY
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Posted 88 ARO

SPONSORED PROJECT TERMINATION

Date: April 28, 1977

8436-2

Project Title: Analytical Investigation of External Burning Behind Bluff-Base Axisymmetric Bodies

Project No: E-16-636

Project Director: Dr. W. C. Strahle

Sponsor: U. S. Army Research Office

Effective Termination Date: 9/30/76

Clearance of Accounting Charges: 9/30/76

Grant/Contract Closeout Actions Remaining:

- __ Final Invoice and Closing Documents
- __ Final Fiscal Report
- X Final Report of Inventions — Sent to ARO in Nov '76 ~~Requested 29 Oct 76~~ No action? Correct!
- __ Govt. Property Inventory & Related Certificate
- __ Classified Material Certificate
- __ Other _____

Assigned to: Aerospace Engineering (School/Laboratory)

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- Other _____

CA-4 (3/76)

PROGRESS REPORT

1. ARO PROPOSAL NUMBER: 11296-E

2. PERIOD COVERED BY REPORT: 10/1/73 to 3/31/74

3. TITLE OF PROPOSAL: "Analytical Investigation of External Burning behind Bluff-Base Bodies"

4. CONTRACT OR GRANT NUMBER: DAHC04-74-C-0038

5. NAME OF INSTITUTION: Georgia Institute of Technology

6. AUTHOR(S) OF REPORT: Warren C. Strahle

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

NONE

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

Dr. Warren C. Strahle, Principal Investigator

Mr. Gopal Mehta, Graduate Research Assistant

No degrees awarded

Dr. Warren C. Strahle
Georgia Institute of Technology
Atlanta, Georgia 30332

The boundary layer equations for the near wake have been written for a turbulent Prandtl number of unity, and the eddy viscosity model chosen for axisymmetric flow is that of Schetz, modified to a form equivalent to that of Alber, and with numerical constants chosen to recover known results for an incompressible free shear layer. The profiles selected for the integral approach are those of Green to start the numerical integration from the base toward the critical point. The integral equations chosen are a) continuity, b) momentum, c) energy, d) first velocity moment of momentum, and e) a momentum equation integrated from the axis to the dividing streamline. To this system must be added the behavior of the exterior flow. For checkout purposes a constant pressure exterior flow has been assumed. Under this set of assumptions the problem has been programmed and the integration has proceeded smoothly to the point where the shear layer intersects the axis. As expected, the reversed flow velocities are extremely high (near sonic) as compared with the two dimensional case.

The next step is to add a modified method of characteristics to the treatment of the exterior flow and to switch to a different set of profiles downstream of the point of intersection of the shear layer with the axis, since those of Green are inadequate to represent the actual physics of the downstream reattachment process.

So far the chosen approach is yielding results smoothly and in accord with physical experience for the turbulent, axially symmetric base flow.

E-16-636

PROGRESS REPORT

1. ARO PROPOSAL NUMBER: 11296-E

2. PERIOD COVERED BY REPORT: 4/1/74 - 9/30/74

3. TITLE OF PROPOSAL: "Analytical Investigation of External Burning behind Bluff-Base Bodies"

4. CONTRACT OR GRANT NUMBER: DAH C04-74-C-0038

5. NAME OF INSTITUTION: Georgia Institute of Technology

6. AUTHOR(S) OF REPORT: Warren C. Strahle

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:
   a) Strahle, W. C. Mehta, G., and Hubbart, J. E. "Progress on a Base Flow Model for External Burning Propulsion," Proceedings of the Workshop on Aerodynamics of Base Combustion, Purdue University, May 29-30, 1974.
   b) Strahle, W. C. and Mehta, G., "Turbulent Axisymmetric Base Flow Studies for External Burning Propulsion," Presented at 11th JANNAF Combustion Meeting, Pasadena, September, 1974. To be published*(see bottom

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

Dr. Warren C. Strahle, Principal Investigator
Mr. Gopal Mehta, Graduate Research Assistant
No degrees awarded

*in meeting proceedings.

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Atlanta, Georgia 30332

11296-E

BRIEF OUTLINE OF RESEARCH FINDINGS

Extreme difficulties have been encountered in the downstream integration of the near wake equations coupled to an approximate method of characteristics for the adjacent inviscid flow. These difficulties have severly restricted progress on the case of a non-reacting, axisymmetric base flow.

In the integral method chosen, three sets of velocity and enthalpy profiles have been tried and several sets of moment equations have been investigated. In all cases a singularity is reached in the equations after downstream integration a distance of the order of 1 to 2 base radii. This singularity is reached before the reversed flow velocity has attained its maximum negative value, so the singular point is substantially upstream of the rear stagnation point. The singular point is not a saddle point and cannot, therefore, be interpreted as a Crocco-Lees critical point. Such a singularity has never been encountered in prior two dimensional studies of base flows and its occurrence here must therefore be a peculiarity of the axial symmetry.

In order to investigate the cause of the difficulty assumptions of adiabatic flow and a Prandtl-Meyer exterior flow are being made to reduce the system of equations to three ordinary differential equations rather than five. A phase plane solution is under investigation to determine the origin and type of the singular point. It is currently believed that the origin of the difficulty lies in the attempt to solve for the reversed flow velocity while using equations (boundary layer) which are too inaccurate to recover the details of the reversed flow region. It is consequently anticipated that a set of velocity profiles will have to be chosen that link the reversed flow velocity to the profile shape. This will drop one differential equation and make the problem simpler while the solution will lose the ability to predict the reversed flow velocity. Nevertheless, a solution will emerge that can predict the base pressure and pressure distribution.

Abstract for publication 7b

ABSTRACT

Progress is described on a model of the turbulent axisymmetric base flow behind bluff-base bodies. The purpose for the model is to provide an analytical basis for later incorporation of external burning and base injection effects upon the base flow. An integral technique is used for solution of the problem. At the current time, however, extreme difficulties are being encountered in the choice of field variable profiles to insert in the integral technique. Several choices of profiles and governing moment equations are yielding a singularity before the rear stagnation point is reached in a downstream integration of the equations.

E-76-656

PROGRESS REPORT

1. ARO PROPOSAL NUMBER: 11296-E

2. PERIOD COVERED BY REPORT: 10/1/74 - 3/31/75

3. TITLE OF PROPOSAL: Analytical Investigation of External Burning Behind Bluff-Base Bodies

4. CONTRACT OR GRANT NUMBER: DAHC 04-74-C-0038

5. NAME OF INSTITUTION: Georgia Institute of Technology

6. AUTHOR(S) OF REPORT: Warren C. Strahle

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

NONE

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

Dr. Warren C. Strahle, Principal Investigator

Mr. Gopal Mehta, Graduate Research Assistant

No degrees awarded

11296E

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ATLANTA, GA 30332

BRIEF OUTLINE OF RESEARCH FINDINGS

Following the approach outlined in the last progress report, success has been achieved in obtaining an axisymmetric base flow solution for the non-reacting, adiabatic case. In order to obtain this solution the problem has been completely reformulated, as compared with previous attempts. an approximate transformation from axisymmetric, compressible flow to axisymmetric, incompressible flow has been used, and the velocity profiles used have been taken from similarity solutions to axisymmetric, incompressible wake-like flows.

In the approach chosen, the number of differential equations needed in the integral method has dropped by one, because the profiles chosen carry with them the magnitude of the centerline velocity for a given profile shape. This represents a compromise in the solution technique; it had originally been hoped that the centerline velocity would come out of this solution, but the difficulties encountered have precluded such a solution.

The current solution technique has been successful on a Mach 2.0, sea level case with a zero thickness initial boundary layer. As compared with data the length of the (nearly) constant pressure region is accurately predicted, but the length to the critical point is overpredicted. Furthermore, the base pressure predicted is too high. The shear stress law being used is suspected to be responsible for these errors and this law is currently under review.

The immediate goal is to now come up with a viable shear stress law which will render the solution accurate as compared with data. Then a more accurate inviscid flow solution will be incorporated, since currently an approximation to the method of characteristics is being employed which is now known to contain rather large errors. It has been determined that a coarse characteristics net may be carried along in the computation without significantly compromising computer time while substantially increasing accuracy.

E-16-634

PROGRESS REPORT

1. ARO PROPOSAL NUMBER: 11296-E

2. PERIOD COVERED BY REPORT: 1/1/75 - 9/30/75

3. TITLE OF PROPOSAL: Analytical Investigation of External Burning Behind Bluff-Base Bodies

4. CONTRACT OR GRANT NUMBER: DAHC 04-74-C-0038

5. NAME OF INSTITUTION: Georgia Institute of Technology

6. AUTHOR(S) OF REPORT: Warren C. Strahle

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:

Strahle, W. C. and Mehta, G. K., "Turbulent Axisymmetric Base Flow Studies for External Burning Propulsion", CPIA Publication 261, Vol. 2, p. 441 (1974).

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

Dr. Warren C. Strahle, Principal Investigator

Mr. Gopal Mehta, Graduate Research Assistant

No degrees awarded

11296E

DR. WARREN C. STRAHLE
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ATLANTA, GA 30332

BRIEF OUTLINE OF RESEARCH FINDINGS

The solution procedure settled upon during the previous report period is now yielding excellent results for the adiabatic, axisymmetric turbulent near wake. With no adjustable constants the model is now giving wake structures which agree with limited data in the following respects: a) base pressure, b) length of the nearly constant pressure region, c) overall wake length, and d) pressure overshoot upon reattachment. The difficulties with long wake length, which were reported in the previous period, have been traced to inaccurate curve fitting of profile integral properties with the profile descriptor. This has now been corrected with excellent results.

It has been found necessary to carry a full method of characteristics computation for the external inviscid flow. All approximate methods tried have failed to be accurate in at least one portion of the flow field. It has been found possible, however, to drop the computer time by using only a coarse net of left running characteristics while retaining a fine net of right running ones.

Current effort is centering about inclusion of a rotational characteristics computation to treat the outer portion of the initial body boundary layer and any entropy layers created by injection shocks in the external burning problem. Also, the boundary layer turn problem is being incorporated into the computer program. An error has been discovered in Alber's treatment of the boundary layer turn problem and this is being corrected.

The work over the next report period will center on completion of a) the boundary layer turn problem, b) the rotational characteristics computation and c) a detailed comparison of the computations with experimental data.

E-16-634

PROGRESS REPORT 5

20 COPIES REQUIRED

1. ARO PROPOSAL NUMBER: 71296-E

2. PERIOD COVERED BY REPORT: 9/30/75 - 6/30/76

3. TITLE OF PROPOSAL: Analytical Investigation of External Burning behind Bluff-Base Bodies

4. CONTRACT OR GRANT NUMBER: DAHC 04-74-C-0038

5. NAME OF INSTITUTION: Georgia Institute of Technology

6. AUTHOR(S) OF REPORT: Warren C. Strahle

7. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS PERIOD, INCLUDING JOURNAL REFERENCES:
Strahle, W. C., Mehta, G. K., Hubbartt, J. E., Neale, D. H. and Pronchick, S. W., "Turbulent Axisymmetric Base Flow Studies for External Burning Propulsion," CPIA Publication 273, Vol II (1975) pp. 475-488.
Strahle, W.C., Mehta, G. K. and Hubbartt, J. E., "Progress on a Base Flow Model for External Burning Propulsion," Aerodynamics of Base Combustion (Murthy, ed.), AIAA, New York (1975) pp. 339-348

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

Dr. Warren C. Strahle, Principal Investigator
Mr. Gopal K. Mehta, Graduate Research Assistant

No degrees awarded

11296E

DR. WARREN C. STRAHLE
GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GA 30332

BRIEF OUTLINE OF RESEARCH FINDINGS

A theory of the near wake flow behind bluff-base axisymmetric bodies in supersonic flight, with a fully turbulent boundary layer approaching the base, has been under development for the past two and one-half years. The theory is necessary as the first step in constructing a theory of the effects of external burning adjacent to the near wake on base pressure alteration for propulsive purposes. Currently, the theory is in the final stages of development and comparison with available experimental data. This work is forming the subject for a Ph.D. dissertation.

The analysis is capable of treating the effects of a) flight and vehicle variables, b) the approach boundary layer, c) an entropy layer adjacent to the approach boundary layer and d) base bleed. The theory is, however, restricted to the adiabatic case in its present development and is restricted to cases with a cylindrical body which is sufficiently long that there are no pressure gradients approaching the base region.

The analysis consists of five distinct regions, treated by different analytical methods and joined together by appropriate patching methods. The first region consists of the separation of the approaching boundary layer and generation of the initial conditions for the wake. The second consists of the near wake flow very close to the body, treated under the boundary layer approximation. The third region is a downstream continuation of the second region toward a saddle point singularity (the uniqueness conditions) where patching to the second region is uniquely determined by appropriate patching conditions. The second and third regions are treated by an integral method; the boundary layer approximation is used which has recently been given strong experimental support. An eddy viscosity model is used for turbulent momentum and energy transport which also agrees with experiments in cases where it may be checked against experiment. The fourth region consists of a rotational, but inviscid, layer adjacent to the near wake which contains part of the shed body boundary layer and any other entropy layer adjacent to the body. This fourth layer is treated by the rotational method of characteristics. Finally, adjacent to the rotational layer is an inviscid, irrotational supersonic flow, treated by the method of characteristics.

Related theories have previously been developed for the planar case, but it has been found that in each of the regions approximations which worked for the planar case were quite inadequate for the axisymmetric case. Consequently, substantial development effort has been required which is unique to the axisymmetric case. Currently, the theory accurately predicts base pressure, length scale to the rear stagnation point, overall reattachment length scale and axial pressure distribution. The effects of the initial boundary layer thickness and base bleed are currently under investigation.

In contrast to the planar case there is experimental uncertainty on the effects of the thickness of the initial boundary layer on base pressure for axisymmetric flow. This has led to analytical experimentation during the reporting period with the treatment of a) the boundary layer separation, b) the boundary condition between the vicous near wake and the vortical entropy layer and c) the joining conditions between the near wake treatment near the body and the treatment appropriate to the reattachment region. The final form of the analysis will depend upon a choice for adequate agreement with both boundary layer thickness effects and base bleed effects.

During the next report period the theory will be finalized, a report issed and a user's manual for the computer program completed.

Progress Report, E-16-636

GEORGIA INSTITUTE OF TECHNOLOGY
Contract
OFFICE OF ~~RESEARCH~~ ADMINISTRATION
ATLANTA, GEORGIA 30332

REPLY TO: JGB/G 4002.93

29 March 1976

U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709

Attention: Mr. James J. Murray
Engineering Sciences Division

Subject: Research Proposal Entitled, "Analytical Investigation of External Burning behind Bluff-Base, Axisymmetric Bodies"
(Renewal of Contract No. DAHC04-73-C-0038)

Gentlemen:

The Georgia Institute of Technology desires to submit for your consideration the subject proposal prepared by Dr. Warren C. Strahle, Regents' Professor, School of Aerospace Engineering. This is for a continuation of research presently being performed under Contract No. DAHC04-73-C-0038.

We believe you will find the proposal complete; however, if anything additional is desired, please let us know, and we will see that it is furnished promptly. Any matters pertaining to the scientific program or personnel may be referred to Dr. Strahle. Contractual or administrative matters may be referred to the writer. The telephone numbers are (Area Code 404) 894-3032 and 894-4814, respectively.

Also transmitted herewith is one copy of a "Memorandum of Understanding" granting permission for outside evaluation.

We appreciate the opportunity of submitting this proposal and look forward to the possibility of continuing our research with you on this program.

Very truly yours,

James G. Bishop, Jr.
Contracts and Grants Officer

ck
Addressee: 25 copies
Enclosures: Proposal - 25 copies
Memorandum of Understanding - 1 copy